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TESTING AND EVALUATION OF SECONDARY BATTERIES FOR USE IN NORTHERN PHOTOVOLTAIC INSTALLATIONS: PHASE II

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ABSTRACT

This program relates to the computer simulation of battery backed-up photovoltaic systems at remote sites, typically in the Canadian far north. The report describes work done in upgrading the PV Watsun simulation program for use in this application. Extensive battery testing of numerous lead-acid and NiCd batteries at multiple temperatures was performed and the results used to design new battery performance models. The experimental work and its impact, along with other enhancements, upon the development of PV Watsun version 2.0 is discussed.

RÉSUMÉ

Le programme en question se rapporte à la simulation sur ordinateur de systèmes photovoltaiques munis de batteries d'appoint qui seraient installés dans des endroits éloignés, en général dans Grand Nord canadien. Le rapport décrit les travaux effectués pour améliorer le programme de simulation PV Watsun afin de l'appliquer dans cette situation. Des essais exhaustifs ont été effectués sur de nombreuses batteries à l'acide et au plomb ainsi que sur des batteries au nickel-cadmium à différentes températures. Les résultats ont servi à concevoir de nouveaux modèles de rendement pour les batteries. Les expériences et leurs répercussions sur l'élaboration de la version 2.0 de PV Watsun font l'objet d'une discussion et d'autres améliorations sont traitées dans le rapport.

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EXECUTIVE SUMMARY

In the present phase of the program, ORTECH International in collaboration with the Watsun group of the University of Waterloo, conducted a very extensive test program on a long list of lead-acid and Ni-Cd batteries and developed a new battery model which takes into acccunt the temperature sensitivity of the battery at low temperatures. The PV Watsun (version 1.0) software package developed at Watsun was used as the basis for a new simulation program, PV Watsun version 2.0, for PV/battery systems.

The battery simulation is the most difficult portion for a PV/battery system. This is due to its inherent nature as a very history dependent device. As a consequence, not only are candidate mathematical models complex, but selecting tests that will establish what the fundamental components of these models are is very difficult.

Battery history can be divided into four main categories. The aging and the so called memory effect are the longest term effects. Aging will be dealt with in the next phase of this program. The memory effect is not prevalent in lead-acid or pocket plate NiCd batteries used in PV applications. The third long term component of battery performance is its most desirable feature, electrical charge storage. This is characterized by a state-of-charge which increases during charging and decreases during discharging. This component must obviously be modeled. The short term components are transient effects in the range of minutes to milliseconds. These should, on average, not contribute to the overall performance of a battery; the difficulty they present lies in their impact on short term testing.

Unlike battery testing and model development work done by many others, the work done here addresses the effects upon battery performance of temperature down to -40°C. In addition, these tests were performed on ten different brand/models of battery, three of them NiCd, the remainder lead-acid.

Although the testing was performed on industry standard test equipment, the results showed a surprising variability, even between the various tests on the same battery. This can in part be accounted for by weaknesses in the battery test equipment. The data did provide total capacity and some voltage information that formed the basis for designing the temperature dependent components of the battery model. However, additional unanticipated battery testing was required in order to establish some of the more intricate details of battery behavior that would be of value in PV Watsun 2.0.

Although low temperature performance of NiCd batteries is generally accepted as being superior to that of lead-acid, the findings here neither confirmed nor contradicted this. Most of the lead-acid batteries used in these tests were special purpose batteries and performed better than expected.

Due to time constraints, more rigorous experiments were only performed on one each of the NiCd and lead acid batteries and only at room temperature and -10°C. The special purpose laboratory setup for these tests maintained very tight control on the tests and provided very high accuracy data on the parameters that most effectively characterized battery behavior. These parameters included the rate of gassing during the latter phases of charging.

Gassing is important in that it is the major and possibly only significant source of coulombic inefficiency in a battery. Knowledge of the gassing rate at all times enabled us to maintain a very meaningful state-of-charge estimate against which we were better able to interpret the other measured and controlled parameters. The preciseness of and our confidence in this method of battery testing induces us to recommend continued work using this technique.

1. INTRODUCTION

This final report describes the work carried out by ORTECH International on contract serial number 23283-7-6130/01-SZ, "Testing and Evaluation of Secondary Batteries for Use in Northern Photovoltaic Installations", Phase II. The work described here dealt mainly with the performance evaluation of various storage batteries and the development of a modeling program for low power photovoltaic (PV) systems.

Non-conventional power systems are required for sites without access to grid power or where fuel supply and transportation costs are high. Among the potential candidates as a non-conventional energy source, solar photovoltaic generation of electric power is attractive, for environmental and economic reasons.

The extreme climatic conditions in many remote Canadian sites, however, pose unique difficulties. The combined effect of low temperatures, low insolation and remoteness impose a premium on the performance of the PV system and its energy storage facility [1].

At the present time, batteries provide the best form of energy storage because of their availability and relatively low cost. PV systems with storage batteries can free a site from any dependence on diesel generators and transportation of fuel.

However, batteries for remote PV systems must possess high charging efficiency, low self discharge, low maintenance, ability to withstand temperature extremes and to operate at various states of charge. Additional system component data and design criteria, together with appropriate test procedures, are clearly needed by Canadian users and designers. This input is critical for the integration and optimization of PV systems to meet typical northern Canadian conditions.

Earlier work on PV system evaluation and testing, and software development, was carried out mostly by American or European groups [2-4]. In Canada, a survey of PV technology and battery storage was conducted by the Alberta Government telephone company [5], and by NRC [6]. However, these studies did not follow rigorous temperature cycling procedures and the selected conditions were not typical of many Canadian sites.

For the last several years, ORTECH International has been applying its considerable expertise in photovoltaics and battery technology to supply some of the missing data that is required in order to obtain a complete picture of the usefulness of the PV technology. With the sponsorship of Energy, Mines and Resources, Canada (and in close collaboration initially with the Water Survey of Canada and the Atmospheric Environment Service), ORTECH has been surveying and conducting low temperature testing (-40°C) of lead-acid and Ni-Cd batteries suitable for this application [7, 8]. A system simulation program, PVFORM [4] was customized and employed to model the systems under study with solar data obtained in selected sites (Fort Smith and Resolute).

In the present phase of the program, ORTECH International in collaboration with the Watsun group of the University of Waterloo, conducted a very extensive test program on a long list of lead-acid and Ni-Cd batteries and developed a new battery model which takes into account the temperature sensitivity of the battery at low temperatures.

Due to various difficulties with PVFORM, both in its operating characteristics and its applicability to Canadian northern sites, the PV Watsun (version 1.0) software package developed at Watsun was used as the basis for a new simulation program for the complete PV system.

2. OBJECTIVES

The general objectives of the program are to build up expertise and capabilities for the complete laboratory evaluation, testing and simulation of low power PV systems with battery storage. In this phase of the program, (Phase II), the objectives were

i) to continue the battery testing at low temperatures (room temperature to -40°C) employing lead-acid and Ni-Cd batteries,

ii) to develop a low temperature model for batteries and

iii) to integrate this model into a new simulation package, PV Watsun 2.0, for stand alone PV systems that can be used by Canadian designers and users.

3. BATTERY TESTING - METHOD AND EXPERIMENTAL RESULTS

In the evolving process of developing or customizing photovoltaic system simulation packages, it has become increasingly clear that the most difficult and critical portion of the model is the storage battery. This is primarily due to the battery's basic function, that of storage; it is by definition affected strongly by its past history.

Unlike other parts of the system that can be to a large degree simulated as having instantaneous responses, the battery has several levels of memory and thus its immediate response is shaped by its history. There is, for example, a long term component that addresses the issue of battery aging. There is also a medium term component that is present primarily in some NiCd batteries which is routinely referred to as the memory effect. Batteries suffering from this characteristic will, due to shallow cycling, temporarily loose their ability to either relinquish charge in the latter portion of their discharge cycle or accept charge in the latter portion of their charge cycle. The dominant component needed to accurately model performance is the shorter term, state-of-charge component of the battery history. There is also a fourth category of memory that is very short term, minutes to milliseconds in duration. The difficulty with simulating a battery and its various levels of memory is the problem of characterizing its full behavior with tests that can be completed in a reasonable time frame or even within the life-time of the battery.

Additional complicating factors in battery modeling that are important to the modeling of PV systems in the far north are cold temperature performance and the low relative charge and discharge rates of a system with a largely annual cycle. These aspects of battery modeling have rarely been dealt with in detail in other research.

3.1 Multiple Temperature and Type Battery Tests

A very large series of tests have been carried out on a number of lead-acid and NiCd batteries from various manufacturers. The first goal of this testing was to characterize the low temperature performance of batteries. The large number of battery brands and models selected would provide an indication of the variations to be expected in this regard and in particular the relative advantage to the use of NiCd batteries in cold temperature applications.

As well as the effect of temperature on battery performance, more than one charge/discharge rate was used to estimate the impact of low rates on battery performance. Since very long tests would be impractical with the large number of batteries being tested, some degree of data extrapolation was anticipated.

3.1.1 Test Description

Ten different batteries were selected and acquired for testing. Three of them were NiCd and the remaining lead-acid. Most were intended for photovoltaic or at least remote power applications as recommended by the manufacturers.

Manufacturer	Model	Type	Nominal Capacity Amp-Hours	Voltage
Varta	P125	lead-acid	212	6
Marathon	MP80	NiCd	80	6
Delco	Freedom	lead-acid	57	12
C&D	3 DCPSA-9	lead-acid	125	6
Exide	3-DD-5	lead-acid	200	6
Sab Nife	SUN 10-5	NiCd	102	6
PMF	6 PMF 200	lead-acid	192	6
Absolyte	6-8000	lead-acid	155	6
Varta	Bloc Vb626	lead-acid	145	6
Varta	TP90	NiCd	93	6

Table 1 - Tested Batteries

The charge and discharge cycles were controlled during testing by an industry standard battery test system, the Digatron Universal Battery Tester. The equipment was recently upgraded to four banks for this project. The battery voltages and currents during testing were monitored by a Molitek 4032 data logger and the results transferred into Lotus compatible data files for analysis.

Discharges performed at other than room temperature were performed with the batteries operating inside of a Revco Ultralow cold chamber capable of maintaining temperatures down to -60 °C. The test temperatures for all batteries were: room temperature; 0 °C; -20 °C; and -40 °C.

To reduce interaction between the various tests for each battery, all charging was completed at room temperature according to the manufacturer's specifications. It would have been desirable to acquire some charge data at reduced temperatures during these tests, however, time constraints and the number of batteries being tested did not permit the slower charging rates required.

Typical manufacturer's specifications for a re-charge cycle involve charging at a constant current that is defined as fraction of the total battery capacity. The bulk of the charging is done in this mode of control until the voltage rises to a specified threshold. At that point the control mode is switched over to maintain that voltage and the current continually decreases. Typically the manufacturer's specifications require that this be continued until vigorous gassing has begun and then continued for a specified period of time beyond that.

The total charge removed and returned to the batteries was monitored indirectly by way of the voltage and current measurements. However, the standard test equipment did not directly control the amount of charge returned and monitoring was an after-the-fact process done at discrete intervals during the charge cycle.

Test runs were repeated wherever significant over- or under-charging occurred or where anomalies were found in the results. The figures for total charge extracted and returned to each battery and the graphs showing the discharge profiles were provided in several of the progress reports and are reproduced here in Appendix A.

All batteries were tested at the 20 hour discharge rates. Four were subsequently selected and tested at the 100 hour discharge rate.

3.1.2 Test Results

The following tables list the measured capacities of the batteries under test as a function of temperature. For a selected subset of the batteries, the tests were performed for both 20 and 100 hour discharge rates, providing information on the capacity as a function of rate of discharge.

		Amp-Hours			
Manufacturer	Model	Room Temp.	0 °C	-20 °C	-40 °C
Varta	P125	162.2	114.4	47.5	19.3
Marathon	MP80	107.7	81.6	72.0	41.9
Delco	Freedom	67.3	58.2	43.0	24.6
C&D	3 DCPSA-9	175.3	145.3	52.3	16.8
Exide	3-DD-5	124.5	96.3	71.8	11.9
Sab Nife	SUN 10-5	163.8	133.0	85.7	52.6
PMF	6 PMF 200	234.6	220.5	138.2	53.8
Absolyte	6-8000	184.7	159.6	120.3	79.3
Varta	Bloc Vb626	249.0	251.8	142.2	61.3
Varta	TP90	129.9	113.6	95.1	49.9

Table 2 - Battery Capacity vs. Temperature (20 Hour)

		Amp-Hours			
Manufacturer	Model	Room Temp.	0 °C	-20 °C	-40 °C
Delco	Freedom	62.9	37.7	21.9	12.3
Sab Nife	SUN 10-5	139.2	127.5	110.9	102.7
Absolyte	6-8000	220.7	216.6	130.1	113.7
Varta	Bloc Vb626	284.8	248.1	121.6	72.5

Table 3 - Battery Capacity vs. Temperature (100 Hour)

The results were much less consistent than anticipated. The recorded charge and discharge currents as controlled by the battery test equipment were erratic. The irregularities in current control were unpredictable, often for long periods non-existent. Although each of the four banks of test equipment showed some character of their own, the irregularities were present in all of them to about the same degree.

Although industry standard test equipment, we could only draw the conclusion that the units were primarily useful for determining overall battery capacity.

Because of the time constraints and the number of batteries, no low temperature, low current charging tests were done. Because of the erratic current control, no attempt was made to use the high current charging data that was measured in this series of tests.

Although erratic, the current control of the test equipment was generally within 5 or 10 % of the intended current. The fluctuations alone do not explain the degree of variation in the test data. It appears that the battery performance is very strongly influenced by any irregularities in the test procedures such as scheduling delays or over-charging. Since in practical applications similarly unpredictable conditions are to be expected, this may be a demonstration of the unpredictability of battery performance in real conditions.

These results did demonstrate the need for extremely tight control in experiments intended to determine the subtle details and interactions between the mechanisms of the battery.

3.2 Current-Voltage Characteristic Experiment

Testing at multiple charge/discharge rates was intended to provide information on the relationship between current and voltage (I-V). In order to acquire more detailed information on the I-V characteristics of a NiCd, a separate experiment was performed.

A single cell was used to prevent the results from being obscured by the potentially unsynchronized responses of the individual cells. The cell was taken through a full discharge and recharge cycle at its nominal 40 hour rate. The current into or out of the cell and the cell voltage was constantly monitored. Periodically, the cell current was taken to several other values, the

resulting voltage being monitored in the usual manner. Two of the other current levels corresponded to the 10 hour and 160 hour rates. The fourth current level was zero. The accuracy of the tests were compromised by several significant time constants built into the cell's behavior (this is the shortest of the four categories of battery memory effect mentioned in the introduction to this section). Within the accuracy of the tests however, the results do provide some information on the I-V characteristics of a cell as a function of state-of-charge.

3.3 Detailed High Accuracy Tests

From the results of the multiple temperature battery tests, it became clear that at least a few additional specialized experiments would be required in order to ascertain the most relevant mechanisms of the battery behavior to be modeled and their subtle interrelationships. It was difficult to design a concise set of tests that would simultaneously address the many facets of battery behavior discussed in the available literature [9,10,11,12,13]. After extensive discussions between Ortech and Watsun and some initial laboratory experiments at both facilities, the following key components of battery behavior were identified as being of importance for simulating PV systems in the far north.

a. A single overall state-of-charge - the amount of charge that is presently available for discharge under the most ideal conditions to be encountered.

b. The primary coulombic inefficiency (wasted charge) - due to gassing during charging.

c. An I-V characteristic that is more or less continuous through the transition between charging to discharging.

d. Effect of temperature on total charge available during discharge. The charge is not lost at colder temperatures; it is simply not available.

e. Effect of temperature on basic I-V characteristic.

The details of the battery model are described more fully in chapter 7.

The 3DCPA9 lead-acid battery and the Sab Nife NiCd battery were selected for this detailed testing. Single cells were tested to prevent the results from being masked by the potentially unsynchronized responses of the individual cells.

Most of the cell behavior was to be characterized as a function of state-of-charge. Except for the effects of gassing, knowledge of this state-of-charge can be maintained as the integral of charge and discharge current over time. When the cell is gassing during charging, a portion of the charging current is in fact going into generating gas instead of increasing the state-of-charge of the cell. A means of allowing for this correction to the state-of-charge integral had to be established early on in the testing sequence.

To do this, the cells under test were sealed off so that any gas generated would be forced through gas-flow measuring apparatus. The first charge cycle was used to establish the connection between gas flow rate and the portion of the charge current that was actually going into gassing instead of charging. As anticipated, the gas flow rate began about 75% of the way through the

charge cycle and rose continuously to a maximum that would presumably correspond to all of the charging current going into gassing. The stoichiometric equivalent current was in fact in agreement with the actual charge current at full charge.

The literature [12] suggested strongly that at any given temperature the onset and degree of gassing was dependent upon the same internal mechanisms as the cell voltage depended. From a modeling point of view, this would enable the gassing to be treated solely as a function of the cell voltage. The validity of this assumption was almost completely verified during these tests.

The onset of gassing for the lead-acid cell was relatively close to that stated in the literature [12] as was the shape of the measured voltage vs. gassing curve. No such information could be found in the literature for NiCd batteries.

The remainder of the high accuracy test sequence involved cycling up and down the state-of-charge curve of the cell under test at a specific charge/discharge rate (current level) until satisfactory repeatability was demonstrated. Because of the quality of the test apparatus and the care taken in performing the tests, this was fairly easily achieved in a minimum of cycles. Because of the previously determined gassing relationships, the actual state-of-charge of the battery was known at all times (assuming that gassing was the only source of coulombic loss). This cycling thus provided cell voltage as a function of state-of-charge rather than just time for both charging and discharging at the specified current.

There was only sufficient time to repeat the sequence for one other current level. Testing at different currents provides information on the current-voltage relationship and how it is affected by the state-of-charge.

The sequence was also performed at the higher of the two current levels for a cold temperature (-10°C). This provided additional highly accurate, although limited, available-capacity vs. temperature information for this particular cell. More importantly, it provided as yet unavailable data on the effect of cell temperature upon the current-voltage characteristics.

The curves for the single cell charge/discharge data were generated using Hewlett-Packard 6256B power supplies. A resistor was placed in series with the cell to be tested. The power supply was then connected across the resistor and cell assembly and set in the constant current mode. Whether the connection was for charge or discharge, the power supply and cell both drove the resistive load. As the potential of the test cell dropped, the power supply would provide the additional voltage needed to maintain the constant current through the load and hence the cell. In the charge mode, the leads of the power supply were reversed so that the power supply was driving both the load and the charging cell.

The current, measured as voltage across the resistor, and the cell potential were logged on a Molitek 4032 data logger. The logger also provided the switching system for turning the charge or discharge off at the end of a particular cycle.

The gassing rates were determined by collecting the evolved hydrogen gas in a graduated measuring cylinder that was filled with water and inverted in a water tank. The mark used for measuring was placed so that it was even with the water level in the tank. This ensured that there were no errors introduced because of expansion or contraction of the gas due to the weight of water supported by the gas.

The chemical reactions for the production of hydrogen are

$$2H^+ + 2e^- \rightarrow H_2 \quad \text{(for lead-acid)} \tag{1}$$

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^- \quad \text{(for NiCd)} \tag{2}$$

Therefore for each hydrogen molecule produced, two electrons are passed. The charge passed, q is then

$$q = 2nF \tag{3}$$

where n is the moles of charge produced and F is 1 Faraday (96485 Coul/mol). If the ideal gas law is assumed for the hydrogen, then the moles of gas produced is determined by

$$n = \frac{PV}{RT} \tag{4}$$

where P = 1 atmosphere is the pressure, T = 298°K is the temperature and R = 0.082 Atm.l/mol/°K is the ideal gas constant. V is the measured volume in litres. Combining equations,

$$q = 2\frac{FPV}{RT} \tag{5}$$

The current is the derivative of charge passed, so

$$i = \frac{dq}{dt} = \left(2\frac{FP}{RT}\right)\frac{dV}{dt} \tag{6}$$

where i is in Amperes or Coulomb/Second. Finally

$$i = \frac{(2 \times 96485 \times 1)}{(0.082 \times 298)}\frac{dV}{dt} = 7897\frac{Coul}{l}\frac{dV}{dt} \tag{7}$$

The current due to hydrogen production is directly related to the gassing rate.

The lead-acid battery was very well behaved at room temperature. The current consumed by the gassing process was independent of the charging rate. The sole dependence seems to be on the cell potential.

Gassing data on the lead-acid could not be obtained at -10°C because only 0.025 litres of gas was produced over 2 hours. This quantity was too small to allow the rates to be determined.

There was an upward shift in the voltage charge curve at -10°C indicating that, as expected, lower temperatures require somewhat higher charging voltages. This need for higher charging voltage is probably directly related to the lack of gassing. It may be desirable to repeat the cold temperature tests and continue charging to a substantially higher voltage.

The nickel cadmium battery was not as well behaved as the lead-acid. The gassing rate climbed initially after the onset of gassing and then leveled off. It picked up again at a higher voltage and proceeded upwards to the maximum possible for that charge rate. The phenomenon appears to be real as the C/30 gassing rates have essentially the same functional shape as the C/10.

The gassing reaction in the NiCd was suppressed at the lower temperature, but not so much as in the case of the lead-acid. Also the NiCd voltage curve changed substantially between the room temperature and -10°C experiments. In the -10°C experiments, the NiCd curve seemed to lose its abrupt shift in potential when it began to form hydrogen.

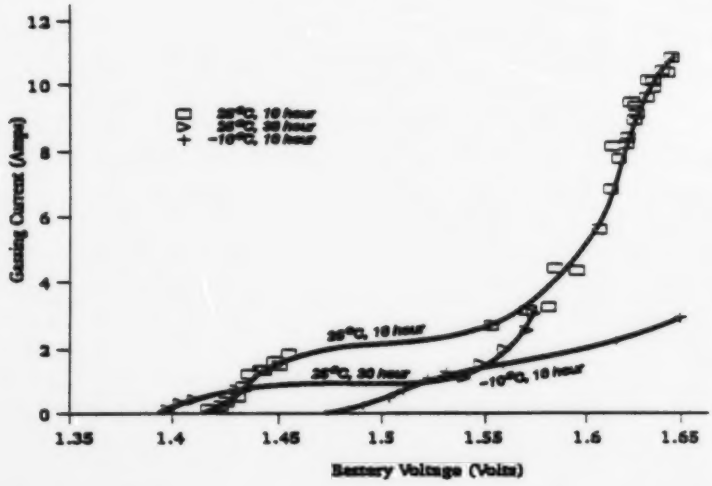
The room temperature charging curves also seemed to have a certain variability in the time at which the curve changes to the hydrogen evolution potential.

For the lead-acid and NiCd cells at various charge rates and temperatures, figures 1 through 3 show gassing current vs. voltage and figures 4 through 9 show voltage vs. time. The reduction in charging current that actually went into storage during gassing had to be compensated for when interpreting the voltage vs. time curves.

In conclusion,

1. The formation of hydrogen in lead-acid batteries is independent of charging rate at room temperature. The same is only true of NiCd batteries to a first order approximation. A second order component related to charging rate may needed in order for the battery model to achieve the highest possible accuracy.

2. The NiCd battery's gassing vs. voltage curve has an as yet unexplained additional characteristic in it.



3. In both batteries the evolution of hydrogen is suppressed at low temperatures. However, in both batteries, a higher charging voltage appears to be necessary at low temperatures and this may explain the lack of hydrogen production.

More experimentation is justified, especially on the NiCd cell.

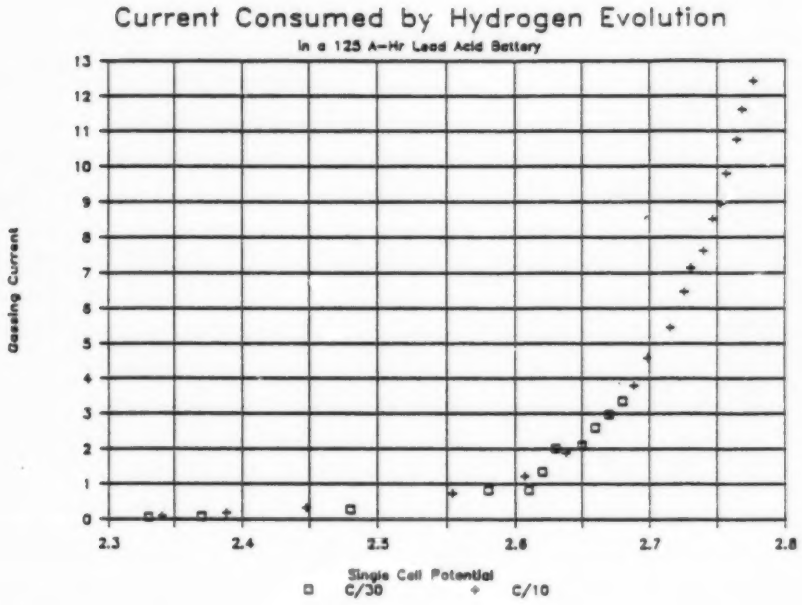


Figure 1 - Lead-Acid Gassing Current
30 hour rate, 25 C and
10 hour rate, 25 C

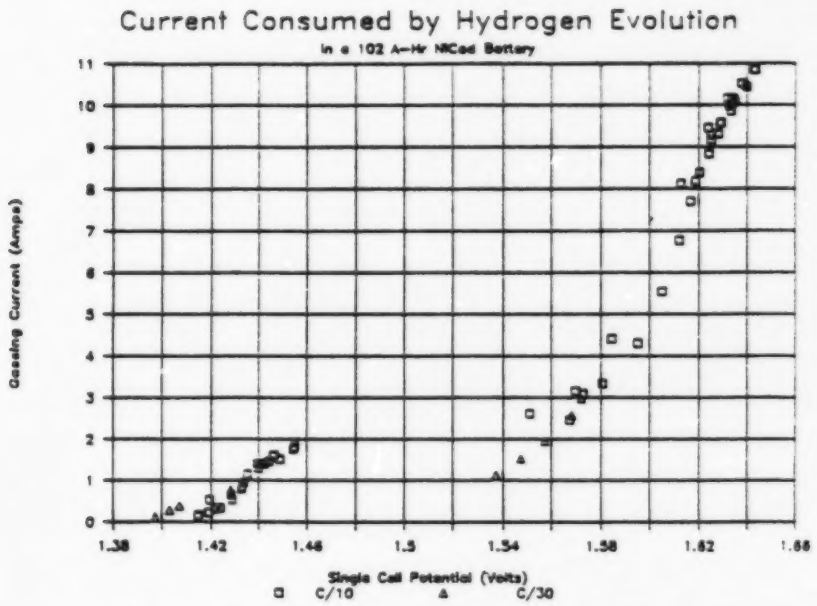


Figure 2 - NiCd Gassing Current - 25 C, 30 hour rate
- 25 C, 10 hour rate

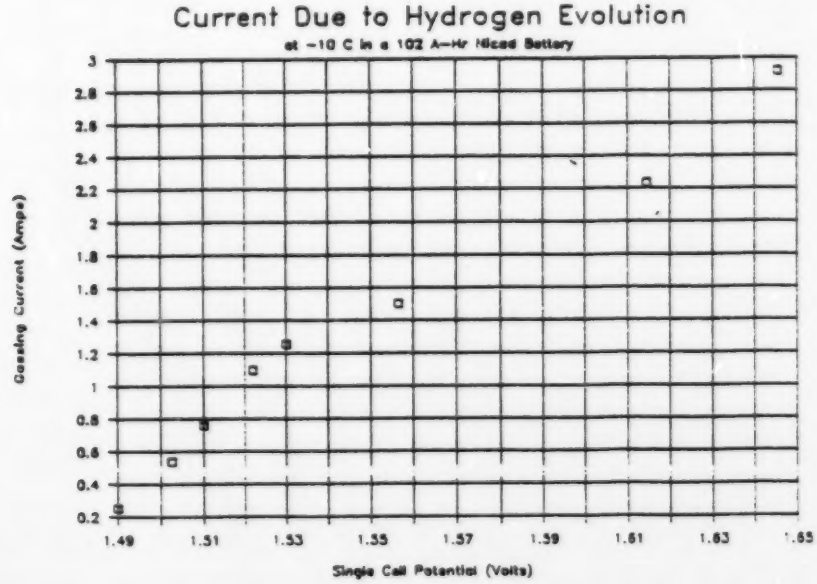


Figure 3 - NiCd Gassing Current
-10 C, 10 hour rate

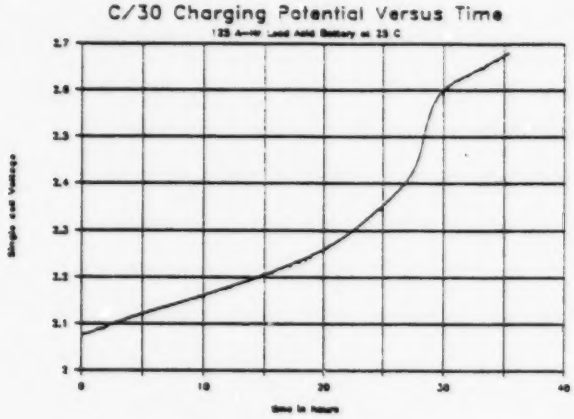


Figure 4
Lead-Acid Charge
30 hour rate
25 C

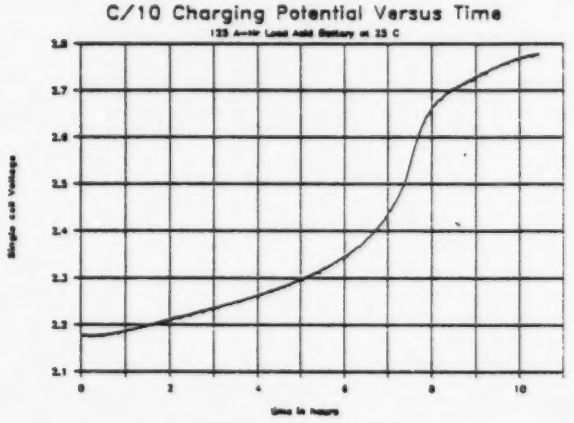


Figure 5
Lead-Acid Charge
10 hour rate
25 C

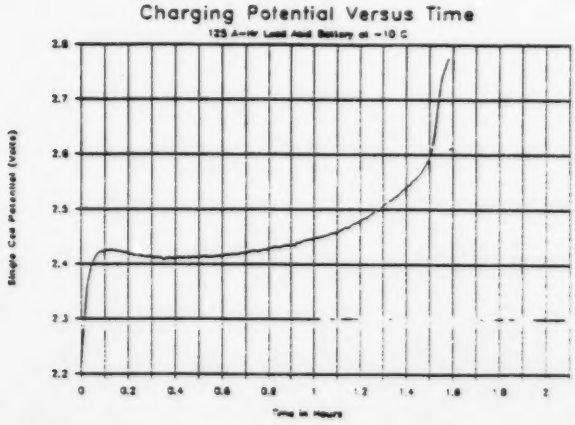


Figure 6
Lead-Acid Charge
10 hour rate
-10 C

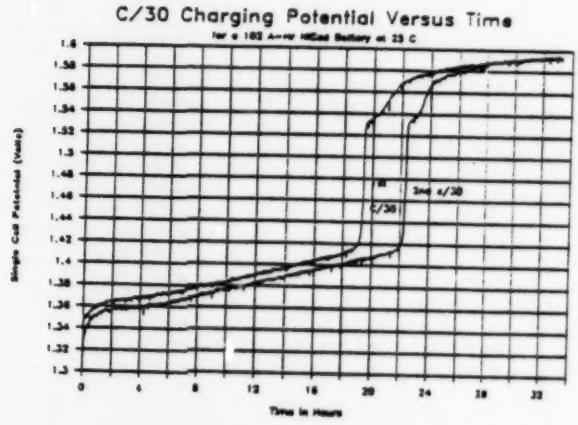


Figure 7
NiCd Charge
30 hour rate
25 C

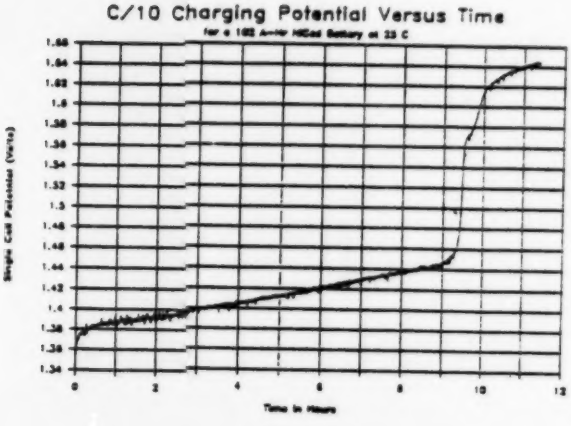


Figure 8
NiCd Charge
10 hour rate
25 C

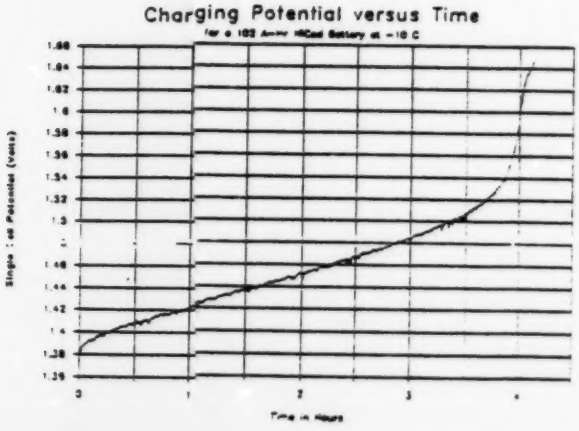


Figure 9
NiCd Charge
10 hour rate
-10 C

4. BATTERY SPECIFICATION

Although the battery tests done in this program took place over the course of a year, their results do not provide information on the aging process of batteries. This is because the wide range of batteries and conditions employed precluded the uniformity of testing that would be required to assess aging processes. Likewise, the assessment of memory effects is not possible with the data collected here. Medium and long term effects such as these must be dealt with separately from this work.

The parameters chosen for this battery specification were targeted for use with the battery model of PV Watsun II. However, consideration was given to the fact that much of the information ideally provided to this model may be very difficult to acquire in practice. More than one level of detail has been included in the spec so that the user of the simulation software can make use of it almost immediately and then fine tune the simulation as familiarity of the package develops and as more detailed battery data is acquired.

Battery data could come from a number of sources. Probably the most convenient of these would be the manufacturer. Generally however such data is devoid of any information on temperature dependence or of the more intricate details that are a function of state-of-charge. As a minimum, the manufacture's spec will provide the nominal capacity and operating voltage. This information along with the battery type will enable the battery model in PV Watsun II to at least make a reasonable simulation of the battery's behavior within the PV system.

Potentially much more detailed information may be available for any given battery from other sources. Because of the large number of parameters and interrelationships that characterize battery behavior, the range of meaningful measurements and tests that can be performed is huge. It is unlikely that tests done by any given third party would provide the simulation parameters directly compatible with PV Watsun II. Some degree of interpretation will invariably be required to extract the appropriate parameters from the data available from such sources.

The ideal source of battery performance data will naturally be tests performed according to the specification defined here, probably done by or commissioned by the user.

5. EXTRAPOLATING SHORT TERM DATA

We would have liked to have been in a better position to comment on the validity of using short term test results to predict the long term performance of batteries. Thus far it appears that this can be done with a reasonable degree of relevance. However, the large number of batteries tested only permitted medium and short term testing.

Data in the literature [13] did suggest the possibility of a nonlinearity in the current-voltage characteristics at very low current levels. If there is reason to believe that long term testing must be done to assess a battery, this or the effects of self-discharge would likely be the justification.

These issues are being addressed in the next phase of this program.

6. COST EFFECTIVENESS OF LEAD-ACID VS. NICD

The differences in low temperature performance of NiCd batteries and lead-acid batteries was not as stark as had been hoped. Variations in test results from battery to battery of the same type were about as large as overall variation between types. This was due to exemplary performance by some of the special purpose lead-acid batteries. In addition some of the NiCd results were disappointing due to sample flaws, weaknesses in our testing or due to mechanisms as yet not compensated for during testing.

Due to this we are not in a position to argue strongly that NiCd batteries are likely to be an advantage in remote PV installations. It can still be suggested that at sites where access is very expensive, the potentially better low temperature performance and longer life may justify the extra expense. The battery lifetime issue will be addressed in the next phase of this program.

7. MODEL DEVELOPMENT

7.1 Meteorological

The modeling of radiation data has three main components:

a. direct radiation;

b. diffuse radiation; and

c. ground reflected radiation.

The representation for the direct component was accurate as it was in the previous version of PV Watsun.

The diffuse component did have a very significant shortcoming in that it was assumed to be isotropic. This portion of the model is being upgraded by Watsun. The current revision has been run in parallel with the old and the diffuse component appears to be much more accurate, showing generally lower contributions. Fine tuning of this model will continue beyond this contract.

The ground reflected component (albedo), although not particularly rigorous, was considered adequate for this application.

An incident angle modifier must be applied to the direct component of radiation. The coding for this will be extracted from the Watsun Thermal package and is judged to be more than adequate.

Only a fixed array-mounting orientation is modeled in PV Watsun 2.0. This is all that would likely be present at remote, unattended sites.

7.2 Photovoltaic Array

Photovoltaic array behavior is quite well understood and documented [1,4,5,6,8]. Unlike the battery, the array has essentially an instantaneous response to its environment (incident radiation, air temperature and net electrical load). Because of its relative simplicity, any improvements that could be made in the photovoltaic array model over what existed in the previous version of PV Watsun were judged to be small compared to potential improvements that can still be made to the battery model. Thus after reviewing the model, no further effort was put into enhancing it.

The array model assumes a peak array efficiency dependent only upon temperature, and characterized by a linear relation relating array output power to incident radiation level. It is assumed to operate as a current source in the region between the maximum power point and the maximum current point. As such, for any given incident radiation level and cell temperature, the output current of the array is constrained within a narrow band over a large voltage range. The battery by comparison operates largely as a voltage source. Thus as a gross approximation, in a direct coupled system, the current available to the load is determined primarily by the array and the voltage is determined primarily by the battery.

7.3 Battery

By far the greatest proportion of the development effort for PV Watsun 2.0 was in the battery model. As mentioned at the start of chapter 3., the primary reason for this emphasis is the battery's functional dependence upon its long, medium and short term history. By comparison, other components of the system have a relatively well defined functional dependence upon only instantaneous external stimuli.

Additional complicating factors in battery modeling that are important to the modeling of PV System in the far north are cold temperature performance and the low relative charge and discharge rates of a system with a largely annual cycle. These aspects of battery modeling have rarely been dealt with in detail in other research [8,11,12,13].

The following sections describe the battery theories and the battery model that was developed from them for use in PV Watsun 2.0. The model is largely phenomenological in nature in that many of its components characterize observed phenomenon rather than physical theory. Note the distinction made here between describing our full understanding to date of battery behavior and describing the model we have chosen to represent it.

7.3.1 Battery Theory

The battery model in PV Watsun 2.0 was built upon a number of existing theories and models developed by others in the battery field as well as upon our own observations and ideas. The following contributions by others have been fundamental in the development of our thinking to date.

A set of electrochemical equations for battery discharge were formulated by Shephard [9]. These equations primarily describe voltage in terms of the electrochemical processes, but were developed only for the discharge portion of the cycle. A numerical method for fitting the proposed equations to battery discharge test data was also developed.

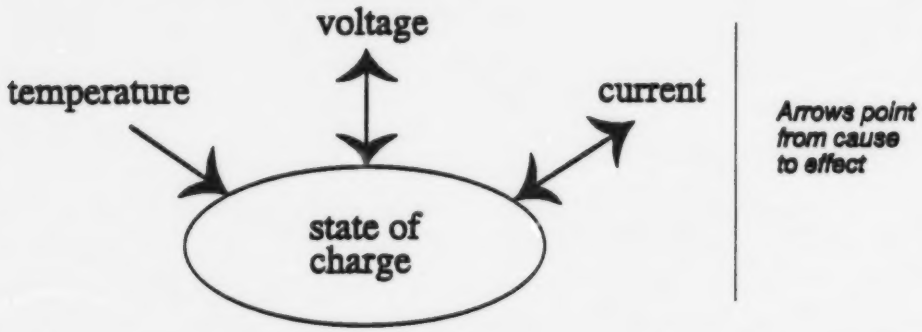
Extensive testing of batteries at the Battery Energy Storage Test (BEST) facility in the United States contributed to the development of an equation to describe discharge [10]. The form of this equation is modeled after Shephard's work while parameterization was facilitated by the extensive testing done at BEST. This model proved to be valid over a wide range of discharge conditions, was computationally simple, and utilized parameters related to observable quantities describing cell performance. This model did not however take account of temperature.

The discharge equation from BEST [10] was generalized to include voltage characteristics during charge, temperature effects, capacity for charge and discharge, and finally charge efficiency [11]. The latter was related to the charging current and the charge already stored. Also included was a simple model of the effects of cycling upon battery life.

Bader gave details of an electronic state-of-charge indicator [12]. Incorporated into this is the result of practical investigations: the quantity of gas evolved from a lead-acid battery may be considered to depend solely on the terminal voltage. A function is presented relating the amount of current contributing to gassing to the difference between the terminal voltage and a predetermined gassing onset voltage.

7.3.2 Primary Components of the Battery Model

The external variables of the battery are the voltage at the terminals, the current through the terminals (positive for charge, negative for discharge), and the temperature. The primary internal variable is the state-of-charge.



The battery interfaces electrically to the other components of the photovoltaic system through its current and voltage. At no time is either variable forced by the battery model to take on a particular value. Rather, at any given battery temperature and state-of-charge, they are constrained to have a certain interrelationship with each other.

In PV Watsun 2.0, this relationship is modeled by defining an internal voltage and internal impedance. The external voltage and current are then in most cases related in a simple, linear manner using Ohm's law. Since the modeling mechanisms in PV Watsun 2.0 require iteration, the simplicity of this current-voltage characteristic is important for computational efficiency. The linear and continuous nature of the relationship also enhances convergence during the iterative process.

The internal voltage and internal impedance are modeled primarily as functions of the state-of-charge of the battery. These functional relationships are then modified by temperature, in a sense providing a family of curves for each.

The state-of-charge is defined as the fraction of full capacity as measured at room temperature that is available for discharge at room temperature. Thus even when the battery is cooled so that less charge is available, the state-of-charge remains the same corresponding to the fact that if warmed, the charge would again become available.

The internal variable, state-of-charge, is the memory component of the battery. It is maintained by keeping track of the current going into and out of the battery. It is not directly influenced by voltage. The model assumes that except for gassing effects to be discussed below, there are no coulombic inefficiencies (wasted current).

The only other inefficiency assumed is voltaic; the battery voltage during discharge is less than that during charge. This is due solely to the internal impedance.

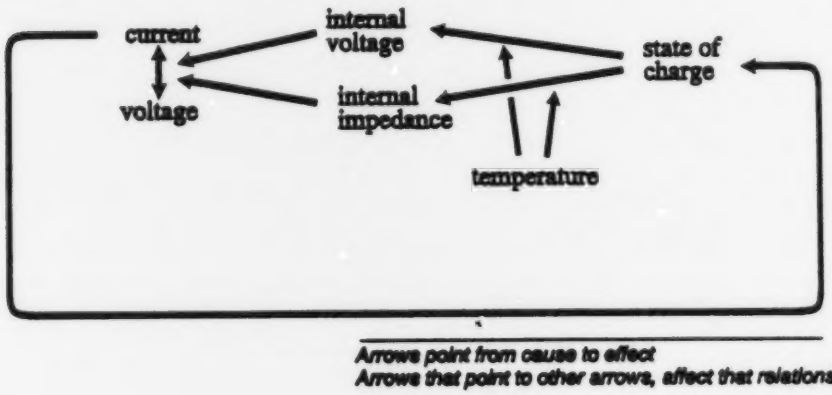
In summary, the primary components of the battery model interact as follows:

a. The interrelationship between the battery voltage and current is defined by the internal voltage and impedance.

b. The internal voltage and impedance are primarily functions of the state-of-charge.

c. The functions defining internal voltage and impedance are modified by the battery temperature.

d. The state-of-charge is determined by the history of current into and out of the battery.



These points are expanded upon and some additional interactions assumed by the model are presented in the sub-sections that follow.

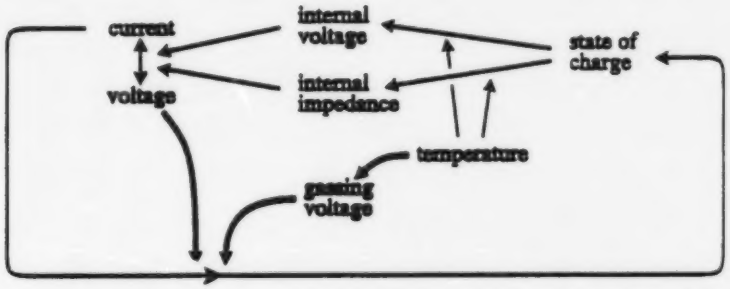
7.3.2.1 Gassing

The only coulombic inefficiency (loss of charge) assumed in the model is that due to gassing. Gassing only occurs during the latter stages of charging.

It is suggested in the literature and supported in our measurements that the proportion of charging current that goes into gassing is dependent upon many of the same factors as the battery voltage is dependent upon. For this reason, the degree of gassing is modeled as if it were a function of the battery voltage. There are two parts to this component of the battery model.

a. Gassing occurs whenever the battery voltage exceeds the gassing voltage, the value of which is dictated solely by the temperature of the battery.

b. The amount of charging current that goes into gassing is solely a function of how far the battery voltage has exceeded the gassing voltage.



The onset-of-gassing voltage increases gently with decreasing temperature. The rate of gassing increases very rapidly beyond this initial gassing voltage.

The modeling parameters in PV Watsun 2.0 permit a second order fit of the gassing voltage to temperature. A higher order polynomial was required to relate the degree of gassing to the difference between the battery voltage and the gassing voltage.

The battery model is intended to be general enough to model both lead-acid and NiCd batteries adequately given appropriate parameters. The NiCd gassing curves are the only point in question here; gassing may have to become at least a second order function of charge rate as well as voltage. Otherwise, however, it appears that the overall structure of the battery model in PV Watsun 2.0 is directly applicable to NiCd batteries.

7.3.2.2 Internal Voltage

The internal voltage of the battery is modeled as a linear function of state-of-charge. At full state-of-charge, it is equal to the gassing voltage. It decreases with decreasing state-of-charge, the slope of which is a battery parameter. With lower battery temperatures, the gassing voltage increases and thus the entire internal voltage curve increases with no change in slope. This corresponds to the increase in electrolyte density with decreasing temperature.

7.3.2.3 Internal Impedance

Beyond coulombic inefficiency due to gassing, the only other inefficiency modeled for the battery is voltaic; the discharge voltage is lower than the charge voltage. In the battery model this voltage difference is due entirely to the internal impedance.

The modeling of internal impedance in PV Watsun 2.0 is relatively complex. Whether charging or discharging, it is characterized by a single baseline value throughout the central range of the state-of-charge. Due to lower ion diffusion rates, the baseline value increases rapidly with decreasing temperature resulting in a generally lower available discharge voltage despite the gently increasing internal battery voltage. Only at very low discharge currents does the battery voltage actually increase with decreasing temperature.

At any temperature there is marked increase in the internal impedance in the latter stages of discharge. This is the factor that limits how much charge can be extracted from the battery at a given temperature. Degradation in performance at lower temperatures is due primarily to a shift in where this effect occurs. At lower temperatures this begins at a higher state-of-charge due to lower ion diffusion rates or possibly localized freezing of the electrolyte. In the model, this temperature characteristic is expressed as a temperature dependent cutoff value for the state-of-charge. The internal impedance approaches infinity as the state-of-charge approaches this cutoff value. This factor is applied only during discharge modes.

When charging, the amount of charge that can be driven into the battery is limited indirectly by a sharp rise in the internal impedance that occurs toward the end of charge. The effect is indirect in that the increasing impedance causes the battery voltage to increase, causing the degree of gassing to increase and thus the fraction of charge current that goes into storage to decrease.

The onset of this increase in impedance is triggered in the model by the onset of gassing, probably due to the reduction in plate area caused by gas bubbles. This onset occurs at different points in the state-of-charge depending upon the charge current. Because of this, when the charge regulator is working in the constant voltage mode near the end of charge, this portion of the battery model must be executed iteratively.

The shape of the impedance vs. state-of-charge curve then proceeds in such a manner that at 100% state-of-charge the voltage predicted results in a gassing current equal to all of the charge current, preventing any further increase in the state-of-charge.

This gassing related component is added to the impedance only during charge cycle.

7.3.2.4 Characteristics Not Included in the Battery Model

Many physical and observed characteristics were excluded from the battery model. These were omitted either for efficiency reasons if it was

felt that their contributions to overall simulation accuracy was not justified or because there was insufficient information available to represent them adequately.

Data in the literature [13] does suggest a nonlinearity in the current-voltage characteristic at very low current levels. Because of the long term nature of the charge discharge cycle in northern PV sites, this could prove to be significant if the system is tightly regulated. We have not acquired sufficiently long term performance data to date to assess the existence or significance of this effect or to model it.

No attempt has been made to model stratification effects or unequal cell performances. In fact, much of our testing has attempted to avoid these effects in order to prevent masking the more fundamental mechanisms of battery behavior.

No attempt has been made to model self heating. In low temperature and low current situations this is very unlikely to contribute significantly to the battery performance unless great lengths are taken to insulate the battery in an attempt to keep it above ambient temperature. If such a design were contemplated, it would become worthwhile to model and compare the exothermic heat source from the voltage drop across the internal impedance and the endothermic absorption of discharge.

Despite the long term nature of simulations of PV systems in the far north, battery self-discharge was not modeled in this version of PV Watsun. Fortunately, the colder temperatures involved greatly reduce the rate of self-discharge.

There are a number of categories of history or memory in a battery. Longest term effects such as battery aging and NiCd memory effects are not modeled here. Very long term testing will be required to measure aging effects and will be is addressed in the next phase of this program.

The so called memory effect is a medium term phenomenon and this is most prominent in NiCd batteries. However, the NiCd batteries proposed for use in these applications would use pocket plate technology which is reportedly free of any of the classic memory effect.

History based on the state-of-charge of the battery is extensively modeled in PV Watsun.

Many of the battery mechanisms have short but finite time constants associated with them. These are of the order of milliseconds through to minutes. It was felt that these would not have a sufficient impact on overall system performance to justify the extra effort and complexity needed to deal with them. Some consideration was given to them, however, as their effects do affect the conduct and interpretation of test procedures.

7.4 Load

The load model in PV Watsun 2.0 has been upgraded to provide two options for characterizing the load. The originally available model parameters were the minimum power needed to meet the essential load requirements, the power required to satisfy the full load and the minimum operating voltage for either of these modes. The second option provides for specification of currents in place of the powers.

The power specification option provides a current-voltage characteristic where the load current varies as the reciprocal of the available voltage down to the minimum operating voltage at which point it drops to zero. The current specification option provides a flat current-voltage characteristic down to the minimum operating voltage at which point it likewise drops to zero.

7.5 Integration

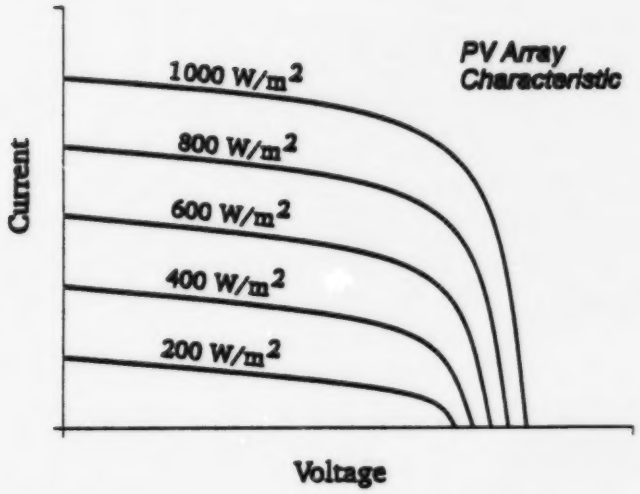
Whereas Watsun PV 1.0 was strictly a power model, with components modeled as efficiencies, Watsun PV 2.0 is a hybrid power and current-voltage (I-V) model of a PV system. Selected and simple components are dealt with as efficiencies, while others are modeled by their I-V characteristics.

Watsun PV 2.0 performs an hour-by-hour simulation: for each hour in the specified simulation period, values of solar radiation, temperature, wind speed, and user specified load are used to simulate performance of the physical system. Unlike traditional hour-by-hour simulation, not all conditions are considered stationary over the hour. Thus although the "physical time step" is one hour a "numerical time step" of somewhat less than one hour is utilized. This is facilitated by the details of the structure of the battery model employed.

This model provides a continuous equation relating terminal voltage to state-of-charge, current and temperature. Consequently, as the battery "charges and discharges" its changing battery terminal voltage may cause the simulation to change modes. During the same hour, the load imposed upon the system may change from a full load to essential load to no load as the voltage drops on discharge. (Statistics on these load modes are one of the key outputs of PV Watsun.) Similarly, in the same hour, switching modes of a charge regulator may be simulated as the battery voltage increases on charge.

The algorithm thus uses a series of numerical time steps to move between the beginning and the end of the hour accommodating these mode changes, while yielding appropriate accuracy. At each mode change point, iteration may be required to determine a new initial operating point.

For example, at the beginning of each hour an initial operating voltage, and current is determined, starting with the array power for the hour, and the battery voltage at the end of the previous hour. Iteration is performed to yield a new initial voltage and array current. Under the assumption that the PV array when electrically clamped to a battery may be approximated as a current source, the array current is assumed to be constant over the hour. Subsequently, iteration may be used at each point of mode change to determine a new initial battery operating voltage.



It has been determined that this hybrid approach combines the computational speed of an hour by hour simulation with the increased accuracy yielded by a continuous system simulation.

Wiring losses in the system are now treated as ohmic losses. In the case of the battery-to-load wiring a line resistance is specified and a power loss is determined from load current delivered. Likewise an array lead-in resistance is specified, and losses computed from the array current present.

The regulator loss is considered a parasitic current in the case of a series or switching regulator, while a shunt regulator is considered to impose a voltage drop in the array circuit with the associated power loss.

8. CONCLUSIONS AND RECOMMENDATIONS

The work carried out in Phase II for the present program consisted mainly of a survey of the performance of various lead-acid and NiCd batteries over a wide temperature range and the design and implementation of a battery model for a new version of a software modeling package. This software package is version 2.0 of PV Watsun and was developed in particular for low power PV systems deployed in the Canadian north.

The objectives of Phase II were achieved in general. Further work is however required to complete the present program as described below.

The battery charge/discharge results showed a surprising variability, even between the various tests on the same battery. This was accounted for largely by the nature of the industry standard test equipment. The data provided total capacity vs. temperature and some voltage information. However, additional battery experimentation (more detailed, higher accuracy) was required to establish some of the more intricate details of battery behavior. In this testing, the gassing rate was monitored to maintain an accurate state-of-charge estimate at all times. This allowed better interpretation of all of the measured battery parameters.

Battery aging processes were outside the scope of the present project; long term effects were thus not considered. The validity of short term test results to predict the long term performance of batteries remains unclear due to the lack of long term testing. Data in the literature suggests certain nonlinearities may exist in the current-voltage characteristics at very low current levels. This would complicate the extrapolation process. Moreover, the effect of self-discharge, even at lower temperatures, should also probably be considered in long term predictions of battery performance. The lack of truly long term test results made the design of a complete battery specification rather difficult as well.

Due to several factors, the low temperature performance of NiCd and lead-acid batteries was relatively similar. The available data does not allow us to argue in favour of either type of battery for low temperature applications. At sites where access is very expensive the decision on battery type will obviously be based on other considerations besides battery unit cost. Battery lifetime is also an important parameter that must be included in the cost/benefit analysis and this will be dealt with in the next phase.

The simulation software developed in this phase has several components: meteorological, PV array, load and battery. Undoubtedly the major achievement of the present work was the development of a new battery model based on the extensive measurements performed on different batteries. The battery was emphasized because of its complexity which is largely due to its functional dependence upon its history. The only characteristics not included in the battery model were those of extremely short or long term duration or whose magnitudes were considered to be small. Battery self-discharge and self-heating were thus not modeled. Stratification or unequal cell performances were not modeled either. Battery memory and battery aging effects were not included in the present version of the model due to the lack of long term data. This is an area where more work is required.

In conclusion, we believe that the data collected and modeling work done on low temperature performance of both lead-acid and NiCd batteries will partially fulfill the requirements of users and designers of systems. It is obvious that more data is required, especially on long term performance, in order to design a complete battery model and battery specification for use with remote PV sites. This version of the complete PV simulation program has pointed out several deficiencies in our understanding

of both theoretical and experimental aspects of batteries that are employed in extreme situations such as those encountered in the Canadian north. On-going improvements and software maintenance will eventually produce a very good simulation tool for broad application in the field.

The preciseness of the detailed method of battery testing developed during this program and the manner in which it relates to the new battery model of PV Watsun 2.0 induces us to recommend continued work using this technique. In particular:

a. Additional testing of the NiCd battery is needed to establish the relevance of the unusual gassing characteristics found in the particular NiCd cell tested.

b. Longer term testing is needed in order to establish the relationship between normal charge and discharge rates and the extremely low rates that might be encountered in a PV system with a year long charge/discharge cycle.

c. Experimentation at a couple of additional temperatures would improve our understanding of the temperature effects on battery performance.

d. The detailed testing should also probably be performed on at least one other brand of lead-acid and NiCd battery in case there are any anomalies in the tested units.

A number of these areas will be addressed in the next phase of this program.

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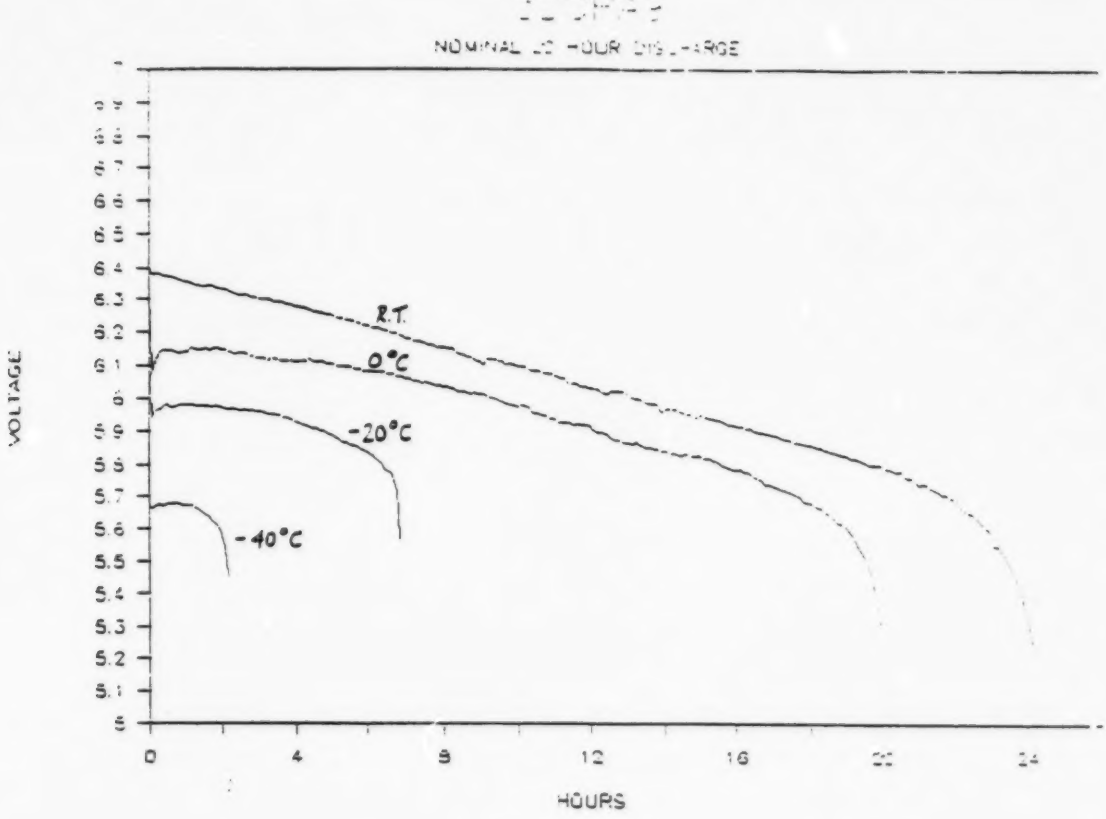
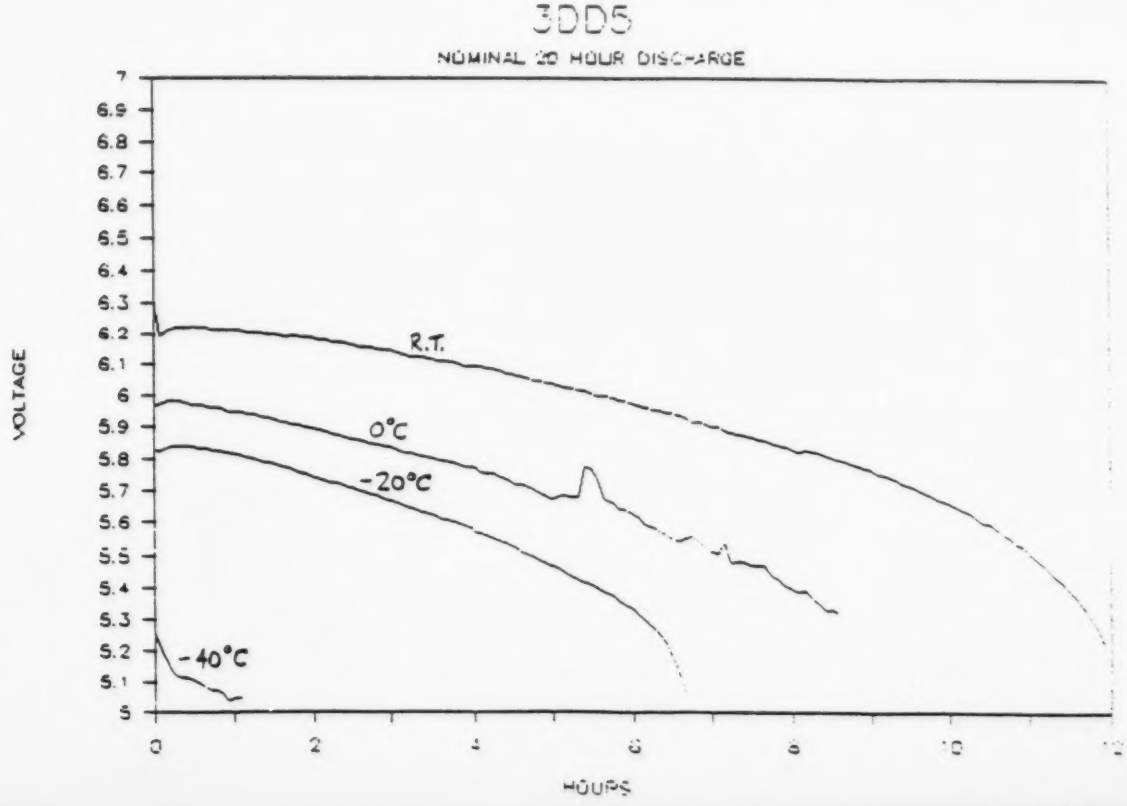
APPENDIX A

Discharge Graphs from

Multiple Temperature and Type Battery Tests

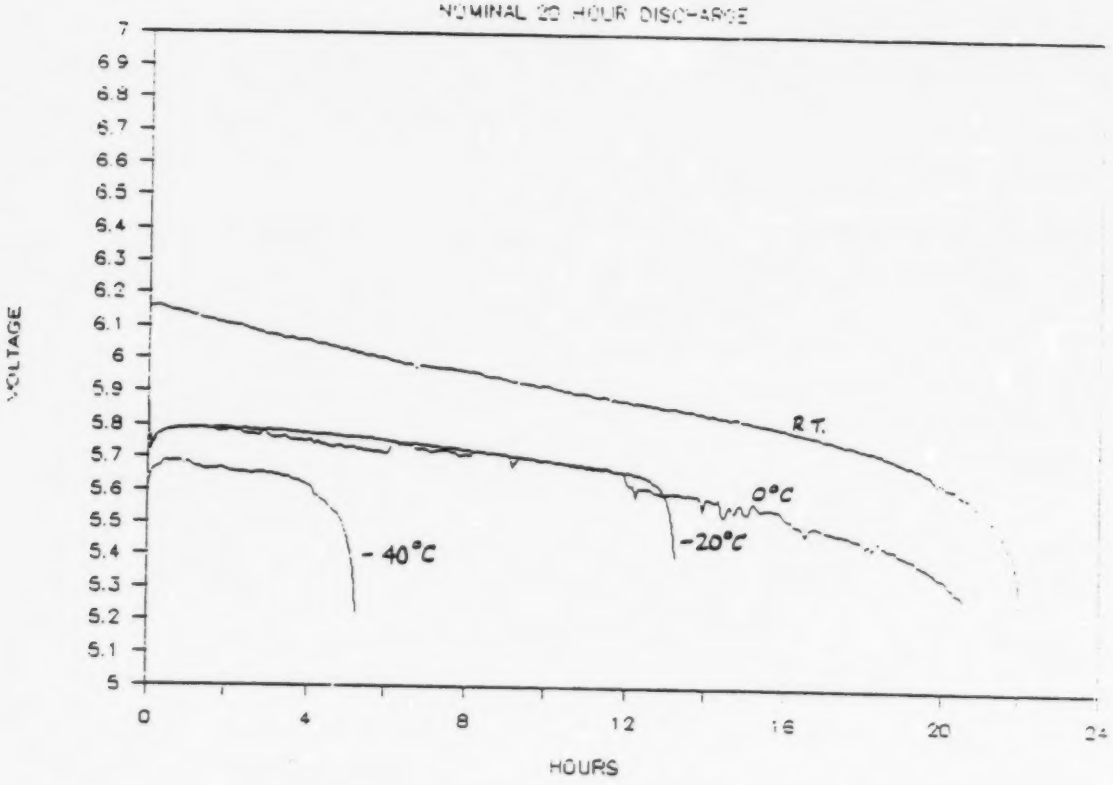
(Section 3.1)


NOMINAL 20 HOUR DISCHARGE
VOLTAGE
HOURS
R.T.
0°C
-20°C
-40°C


3DD5
NOMINAL 20 HOUR DISCHARGE
VOLTAGE
HOURS
R.T.
0°C
-20°C
-40°C

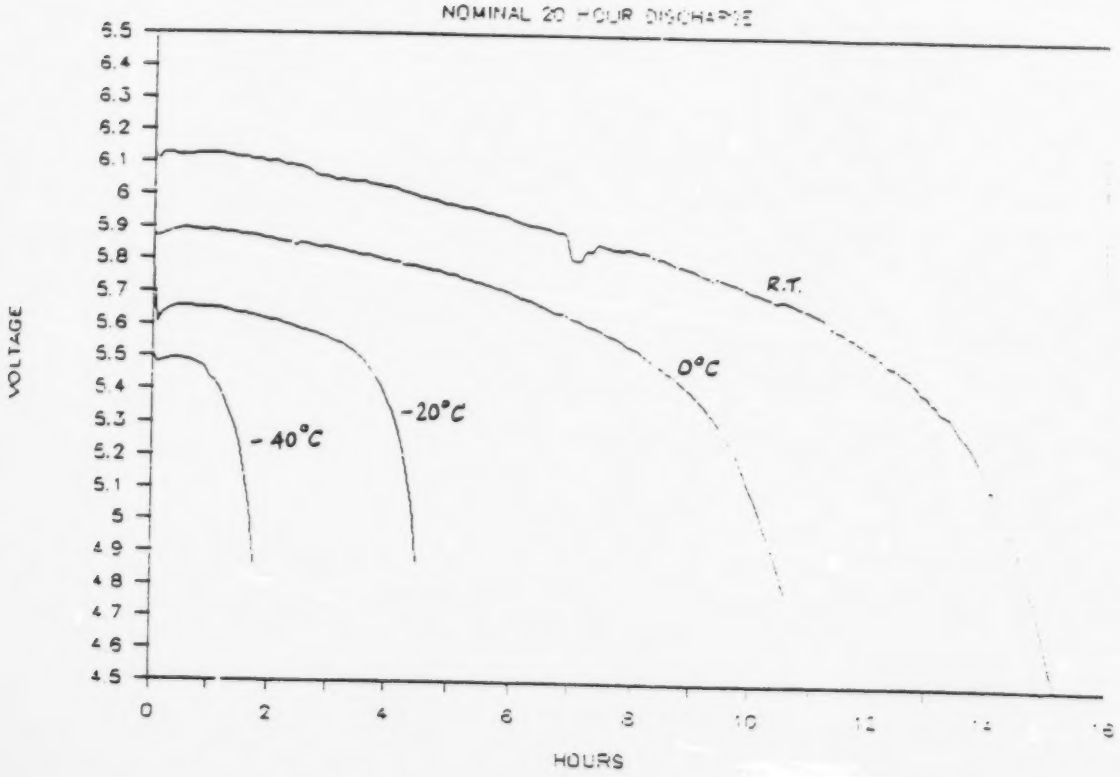
6PMF-200

NOMINAL 20 HOUR DISCHARGE



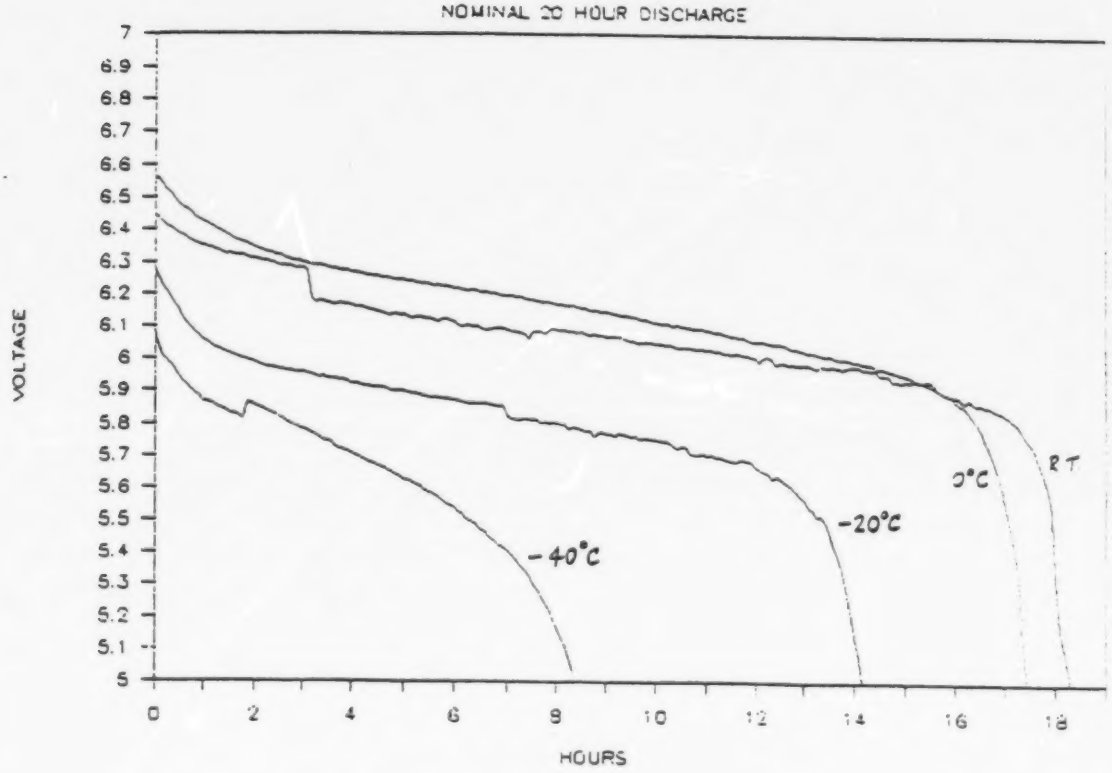
P125

NOMINAL 20 HOUR DISCHARGE



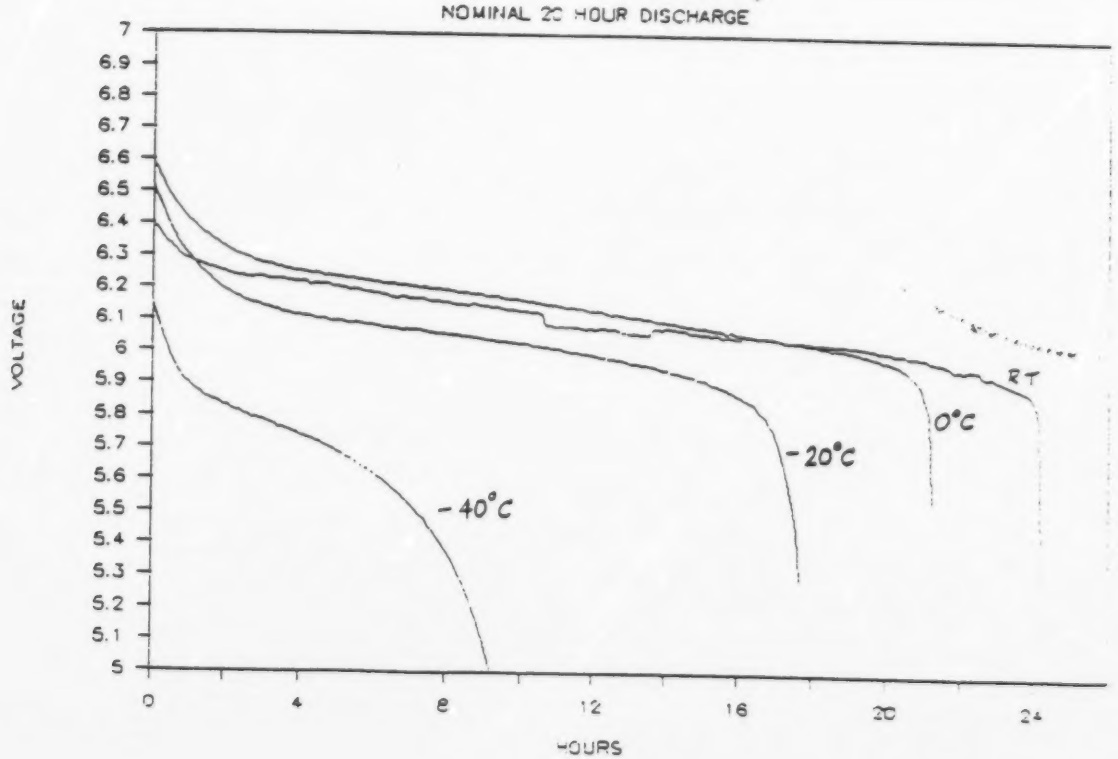
MP80 (NiCd)

NOMINAL 20 HOUR DISCHARGE

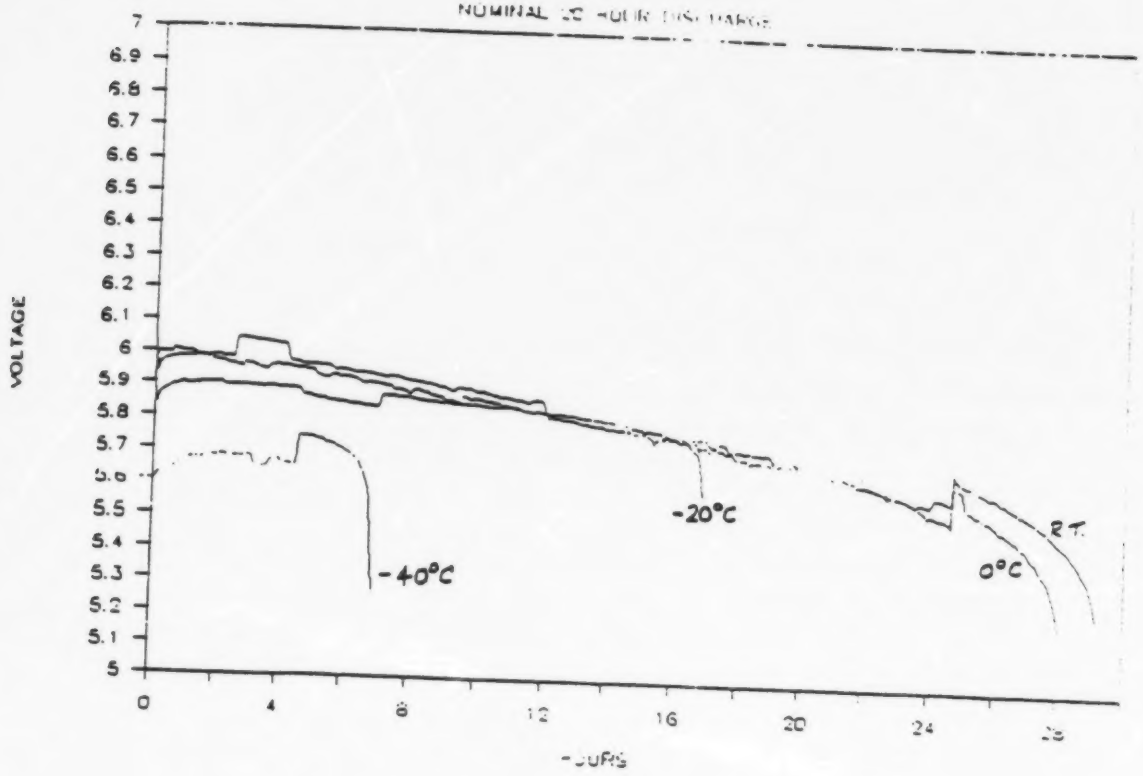


TP90 (NiCd)

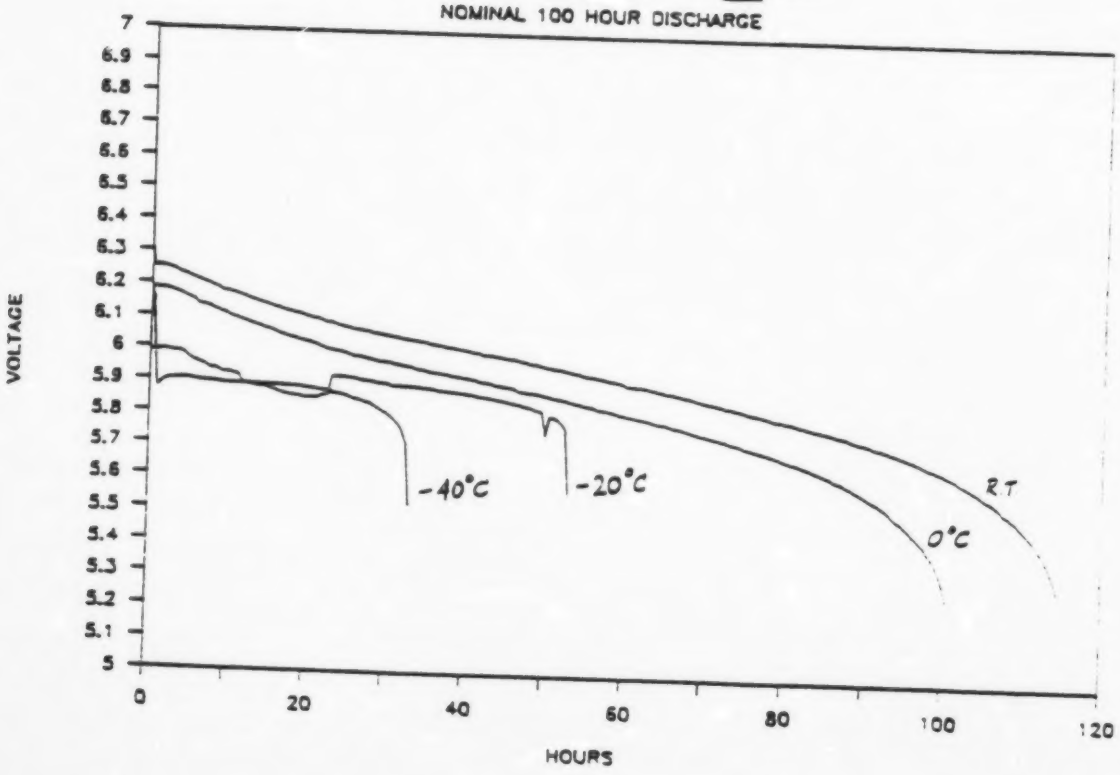
NOMINAL 20 HOUR DISCHARGE



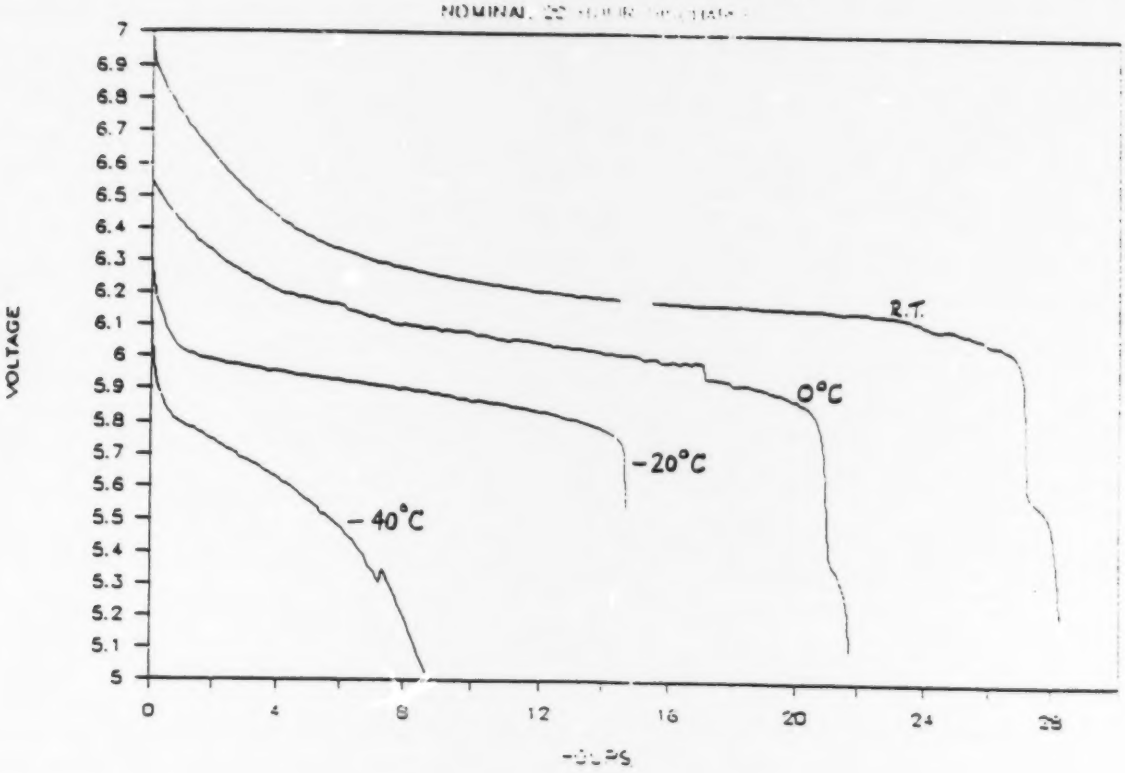
BLOC



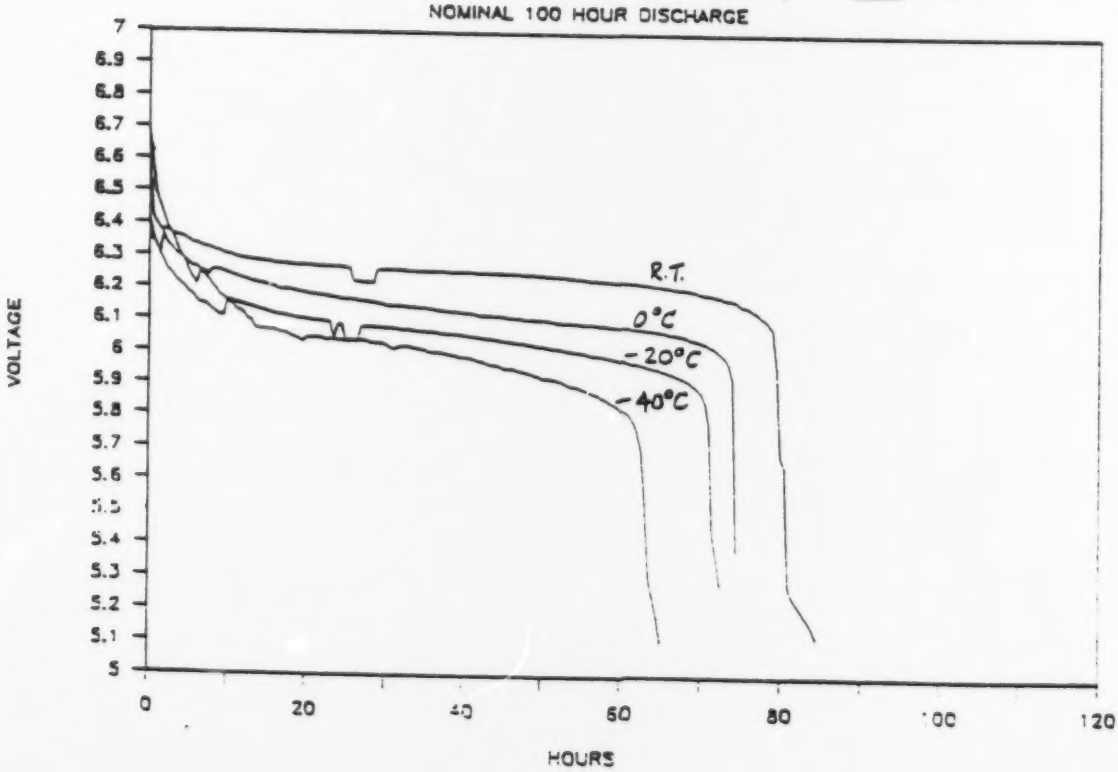
BLOC 100 hour



SABNIFE (NiCd)

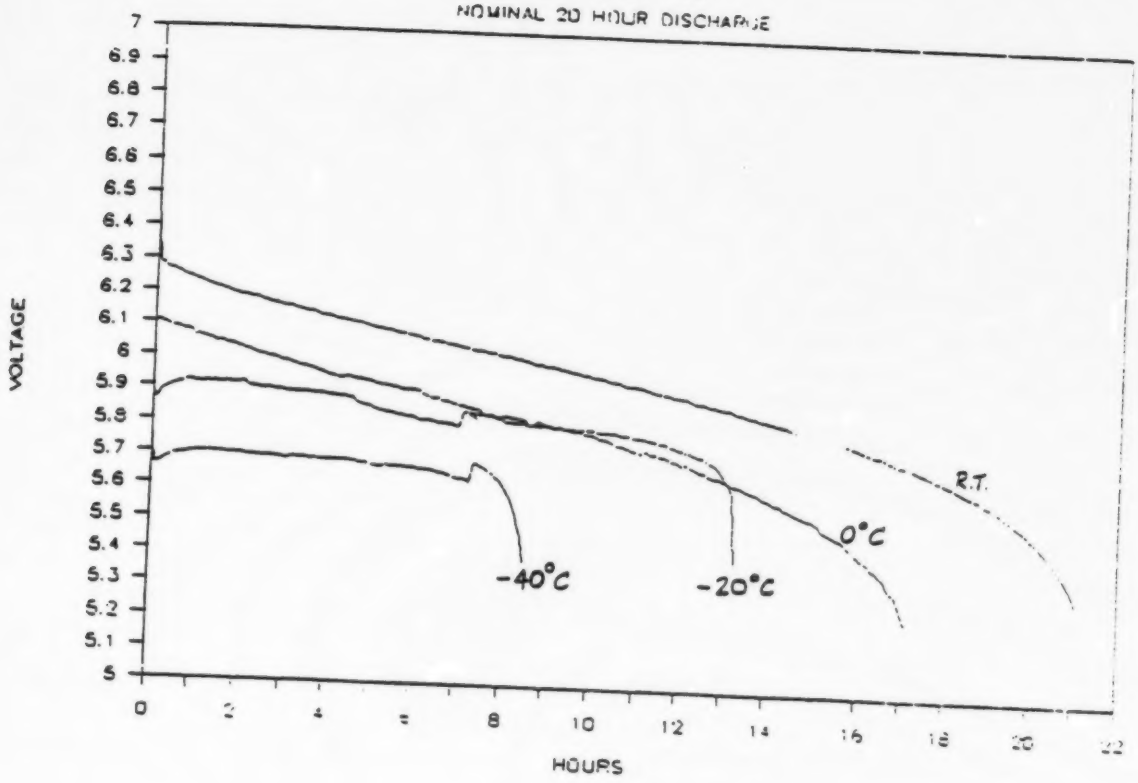


SABNIFE (NiCd) 100 hour



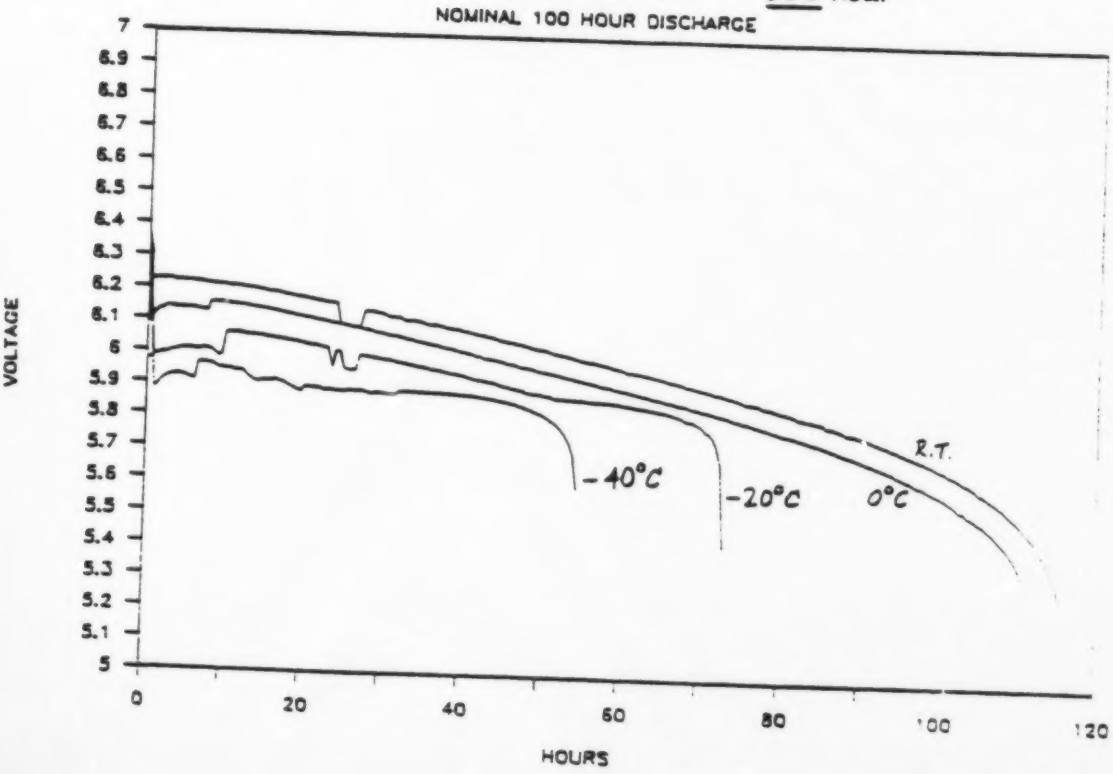
ABSOLYTE

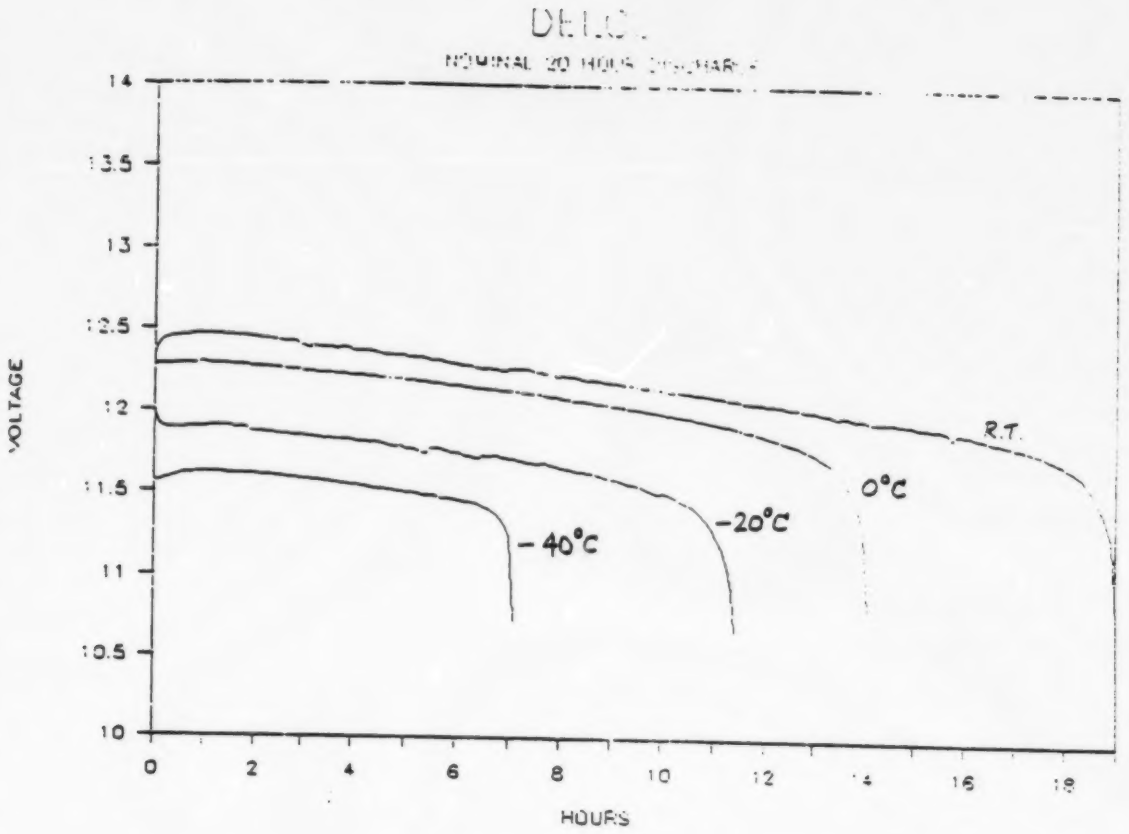
NOMINAL 20 HOUR DISCHARGE

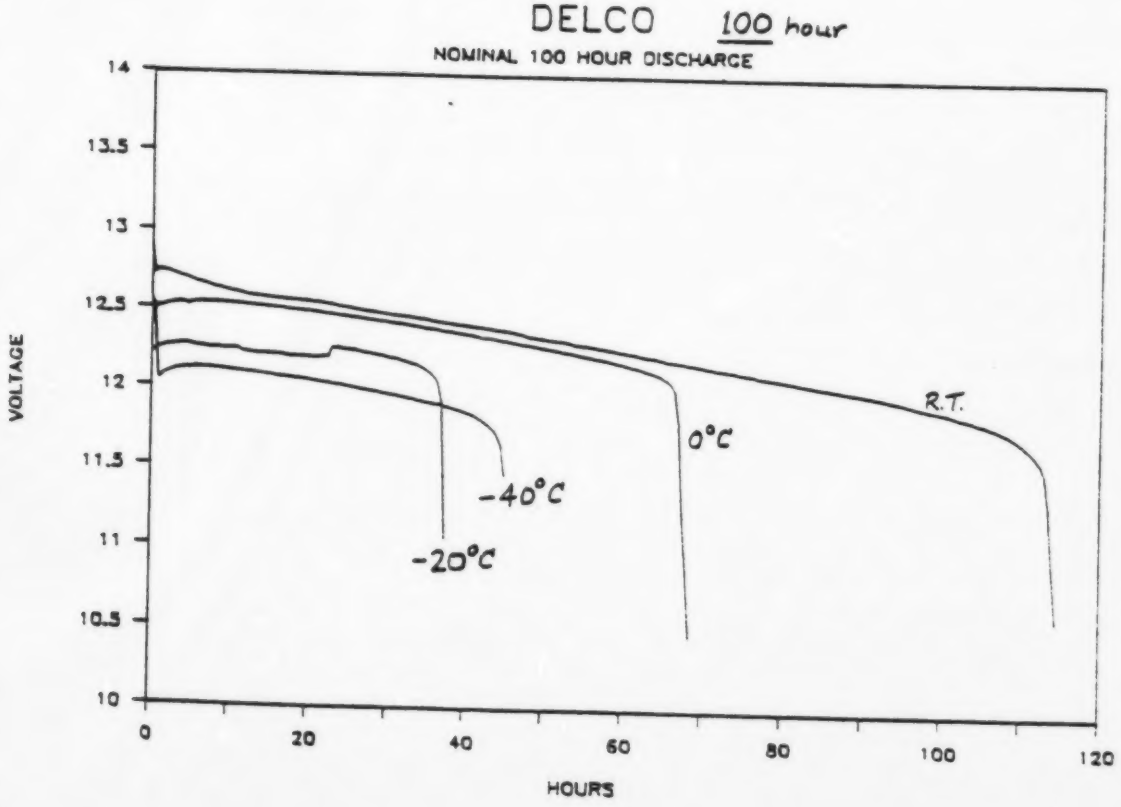


ABSOLYTE 100 hour

NOMINAL 100 HOUR DISCHARGE




DELCO
VOLTAGE
14
13.5
13
12.5
12
11.5
11
10.5
10
0
2
4
6
8
10
12
16
18
HOURS
R.T.
0°C
-20°C
-40°C


DELCO 100 hour
NOMINAL 100 HOUR DISCHARGE
VOLTAGE
14
13.5
13
12.5
12
11.5
11
10.5
10
0
20
40
60
80
100
120
HOURS
R.T.
0°C
-40°C
-20°C